

**University of Washington**  
**Department of Astronomy**  
*Seattle, WA 98195*

This report covers research and other activities during the academic year 1994-1995.

## 1. STAFF AND STUDENTS

During the Academic Year 1994-95, the teaching faculty of the Department included Professors B. Balick, K. H. Böhm, P. Boynton, D. Brownlee, P. Hodge, C. Hogan, G. Lake, B. Margon, G. Nelson, W. Sullivan, P. Szkody and G. Wallerstein. C. Stubbs (formerly at UCSB) joined the faculty, and Hogan succeeded Margon as Department Chair. T. Jacobsen and E. Böhm-Vitense were faculty emeritus. The research faculty members were Drs. S. Anderson, W. Baum, J. Brown, N. Katz and T. Quinn. Postdoctoral research associates were B. Moore and A. Silber. Twenty-three graduate students were registered as members of the Department, and four Ph.D. degrees were granted to: Bryan Miller, currently at the Carnegie Institution, Washington, DC; Liliya Rodrigues-Williams, currently at Cambridge University, United Kingdom; Toby Smith, currently a Post Doctoral Research Associate at the University of Washington, and Nicholas Strobel, currently residing in Olympia, WA. A. Diercks and M. Pratt joined the department as Research Technicians working with Stubbs on his Cosmology Initiative and MACHO projects, respectively. Other MACHO project members who joined the staff are J. D. Reynolds, Senior Computer Specialist, and P. Doherty, Research Engineer. A. Arrington joined the office staff. More information on staff, students and facilities may be found on World Wide Web via URL <http://www.astro.washington.edu>.

## 2. RESEARCH

### 2.1 Solar System

Brownlee is developing a NASA Discovery mission to collect cometary materials and return them to Earth. This mission, STARDUST, has been selected for the fourth Discovery mission. Using a low cost spacecraft developed by Lockheed-Martin Aerospace and managed by JPL, the STARDUST project will collect comet samples during a 6 km/s flyby of comet Wild 2. Over 10,000 particles in the 10 micron to 1mm size range will be captured by impact into ultra low density silica aerogel. STARDUST will also detect and capture contemporary interstellar dust that Ulysses and Galileo spacecraft have recently discovered to be streaming through the solar system.

Reflectance spectra of 15 near-Earth asteroids and three cometary candidates have been obtained by M. Hammergren as part of an ongoing spectroscopic survey of near-Earth objects. The objects were observed in the wavelength range from 3800–10,000 Angstroms using the Double Imaging Spectrograph on the Apache Point Observatory (APO) 3.5-m telescope. Broad solid-state absorption features diagnostic of surface mineralogy have been identified in these spectra, en-

abling the taxonomic classification of these objects as well as providing insights into their compositions. One preliminary result indicates that the asteroid 2062 Aten displays significant spectral differences from an average S-class asteroid. Rotationally-resolved spectra of 433 Eros have also been taken in an effort to map the asteroid's surface composition.

Stubbs, Diercks and Doherty are working in collaboration with K. Cook (LLNL) and E. Bowell and coworkers (Lowell Observatory) to mount a search for Near Earth Objects. The UW group is building a 4K x 4K drift scan CCD camera that will be installed at Lowell Observatory in the coming year.

Smith, working with samples collected by Hodge, completed his dissertation, which produced an analysis of the distribution, chemical nature and total mass of the meteoritic material in the soil surrounding two recent meteorite craters, Dalgara in Australia and Odessa in Texas. He found that the most common type of impact-produced particles are microscopic fragments of the parent meteorite that show modest alteration due to the impact and varying amounts of weathering. Compound-composition spherules, such as are found at Henbury, are rare at these two sites. The total mass of meteoritic material in the soil in each case is more than an order of magnitude larger than the mass of recovered ponderable meteorites from the crater location.

Brownlee and D. Joswiak are collaborating with J. Bradley (MVA Inc., Atlanta) in a project to investigate the properties of "GEMS," a major component of interplanetary dust particles with probable cometary origins. GEMS are typically 300 nm in diameter and they are composed of silicate glass with large numbers of embedded 10 nm rounded grains of iron sulfide and FeNi metal. Gems show internal compositional gradients consistent with sputtering and irradiation before accretion into comets. The size, composition, irradiation history, optical properties and magnetic properties of GEMS are all consistent with the hypothesis that they are preserved samples of interstellar silicate grains.

Quinn and A. Dolphin are integrating the orbits of the planets for the lifetime of the Solar System including general relativity and the Earth–Moon system. This is 1000 times longer than any previous accurate integration. As well as providing a definitive answer to the question of the stability of the planetary orbits, they will gain insight into other fundamental questions of non-linear dynamics and solar system evolution. In particular, the Solar System displays an instability with a time-scale of 5 Myr. What this means for the evolution of the system over 5 Gyr is not clear, but is something they can answer with this integration. Additional products of their research will include: a time history of the Earth's orbital elements to be used in investigation of Milankovitch climate cycles, and a first look at the generic stability of other planetary systems, with an eye toward the relationship of the formation and stability of the Earth to the massive planets that can be detected in other planetary systems.

## 2.2 Stars and Compact Objects

Szkody, in collaboration with E. Sion (Villanova) and M. Huang (Villanova), continued working with HST spectra of the underlying white dwarf in cataclysmic variables. FOS spectra of VW Hyi 10 days after the return to quiescence were modelled with a 22,000K  $\log g=8.0$  white dwarf with oxygen 0.3 solar, nitrogen 5 times solar and other heavy elements 0.15 times solar. A high resolution GHRS observation of the Si IV line indicated a rotational velocity of the white dwarf of  $v \sin i = 600$  km/s. Since this is much less than Keplerian, the low boundary layer luminosity of this system cannot be explained by high rotation. Further FOS data obtained at superoutburst surprisingly revealed 2 components in the absorption lines: a broad component from the accretion disk and a sharp core component that could either arise from gas streams or the white dwarf.

Szkody, Sion and K. Long (STScI) analyzed ASCA data obtained during the quiescence of U Gem. The 2 data sets obtained one month apart showed no flux changes, indicating a constant hard X-ray component with  $kT=8$  keV.

The advantageous scheduling mode of the APO 3.5m telescope allowed the collection of optical spectra along with IUE data throughout the 43 day superoutburst cycle of the unique cataclysmic variable ER UMa by Szkody, Silber, D.W. Hoard, K. Honeycutt (Indiana) and J. Robertson (Indiana). These data showed the typical transitions from an optically thick to an optically thin disk, as well as revealing the short orbital period, which proved that this object is very similar to the normal systems below the period gap except for the very short timescales involved in the supercycle.

Szkody, Silber, Sion and S. Howell (PSI) obtained IUE and optical spectra during the unusually long and large amplitude outburst of AL Com in April. These data are being analyzed to determine the outburst characteristics and cooling curve of this ultrashort period binary in relation to the similar system WZ Sge.

Howell and Szkody completed and published analysis of the superoutburst IUE spectra of SW UMa, BC UMa and TV Crv that showed extremely large wind velocities.

Szkody and Silber obtained IUE observations of 5 magnetic systems (H0459+246, RXJ0515+0105, AR UMa, H1752+081, H0857-242) that showed a wide range of continuum and line fluxes. These data are being fit with hot white dwarfs to determine the temperature of the UV emitting areas.

Collaborations with K.P. Singh, P. Barrett, E. Schlegel (Goddard) as well as V. Pirola (Tuorla Obs) led Szkody, Silber, Hoard, and E. Fierce to the optical identifications of 2 new magnetic cataclysmic variables (J1047.1+6335 and J1802.1+1804), using data from APO and the Manastash Ridge Observatory (MRO) 0.8-m telescope.

Szkody and P. Garnavich (CfA) used APO to obtain high resolution data on the exceptionally long period (8 hr) magnetic RXJ0515+0105 that revealed a multi-component structure. Analysis to determine the locations of each emission region is proceeding.

Hoard and Szkody are engaged in an ongoing investigation of the recently identified SW Sextantis subclass of cataclysmic variables. Time-resolved, high resolution (3800-

7000Å, 2 Å/pix) spectra of four SW Sex stars (BH Lyn, PG0859+415, DW UMa, V1776 Cyg) have been obtained throughout complete orbital cycles of the systems, using the Double Imaging Spectrograph on the APO 3.5m telescope. The spectra will be used to construct both doppler tomograms of the accretion disks in these stars and atmosphere models of the accretion stream + hot spot + disk + WD system.

Stubbs and Pratt contributed to the first publications using the variable star data in the MACHO database, which focussed on the Cepheid variable stars in the LMC. Evidence for overtone pulsations in LMC Cepheids was detected, as well as a sample of over 40 extragalactic beat Cepheids.

Boynnton together with J. Deeter and D. Reiss are continuing their analysis of existing optical photometric data on HZ-Her/Her X-1. Such studies are motivated by their recent work on X-ray pulse profile evolution over the 35 day cycle of this close binary. These GINGA observations have raised the possibility of gaining further information from the optical light curve regarding the geometry and physics of the accretion disk.

Böhm-Vitense and B. Beck-Winshatz in collaboration with N. R. Evans (CFA), K. Carpenter (GSFC) and R. Robinson (GSFC) are continuing their efforts to determine the dynamical masses of Cepheids with blue companions.

Böhm-Vitense is also continuing her studies of chromospheres, transition layers and coronae in F stars.

Wallerstein, Brown, D. Geisler (NOAO) and J. B. Oke (Caltech and DAO) have completed their abundance analysis of red giants in three distant open clusters in the Galactic anti-center direction: Tombaugh 2, Melotte 71 and NGC 2112.  $[Fe/H]$  values are near  $-0.45$ ,  $-0.30$ , and  $-0.10$  respectively. These metal deficiencies are smaller than had been derived by photometry, especially for NGC 2112, for which several red giants were found not to be radial velocity members. For the two significantly metal-poor clusters oxygen was found mildly *deficient* relative to iron in contradistinction from metal-poor field stars in the solar vicinity. For Tom 2  $[\alpha/Fe] \approx -0.1$  while for Mel 71  $[\alpha/Fe] \approx +0.1$ . Hence there appear to be small differences in the chemical history of clusters 2.5-6 kpc further from the Galactic center than is the sun.

D. Zucker, working with Brown and Wallerstein has completed the analysis of six oxygen-poor red giants in Omega Centauri. They have confirmed the oxygen deficiencies first seen by Paltoglou and Norris as well as Norris and Da Costa. In addition they have confirmed that both Na and Al are deficient in the oxygen-poor stars. They have also discussed the origin of the Na and Al excess and have pointed to the great difficulty of enhancing the Al abundance by internal nucleosynthesis and mixing.

Brown, with Zucker and Wallerstein, is analyzing high resolution (35,000) CTIO spectra of signal-to-noise 30-50 of two stars in the relatively young globular clusters Ru 106 and Pal 12. Preliminary  $[Fe/H]$  values for the clusters are  $-1.5$  for Ru 106 and  $-1.0$  for Pal 12. The derived iron abundance for Ru 106 is substantially greater than earlier photometric indications, but is sensitive to the adopted reddening which is substantial and uncertain. Quite surprisingly

(and less sensitive to the reddening) is the  $[\alpha/\text{Fe}]$  value of  $-0.4$  in Ru 106 and  $0.0$  in Pal 12. Thus it appears that the usual excess of the  $\alpha$ -elements of  $+0.3$  or  $0.4$  dex for metal-poor stars is not present in these clusters and that their nucleosynthesis histories may be different from those of other globulars and nearby metal-poor field stars. It is interesting that the motions of both clusters permit them to have been captured by our Galaxy rather than formed in our Galactic Halo.

Wallerstein has obtained high resolution spectra at the DAO of 12 M supergiants in the young open cluster h and chi Persei for the analysis of their lithium lines. He has also been obtaining similar spectra of resolution 35,000 of a number of SC stars to be analyzed in cooperation with C. Abia of the University of Grenada, Spain.

Brown has been using the DAO to observe a number of S stars, both with and without Tc, at the He I line at  $10830 \text{ \AA}$  in coordination with HST observations to study the possible interaction of the cool star with a white dwarf companion.

Silber, Anderson, Margon, and R. Downes (STScI) continued their analysis of HST time-resolved observations of the UV analog of the 71-s low amplitude pulsations of DQ Her seen in visible light. The continuum,  $\text{Ly}\alpha$ , and C IV  $\lambda 1549$  are seen to pulse with amplitudes of a few percent, 16%, and 6%, respectively. The phase of all three of these effects are seen to differ at a statistically-significant level. These phase shifts may indicate that the true pulsation period of the line emission is slightly different from that of the continuum, and thus provide interesting structural data on the locations of the various emitting regions. Using data from the ROSAT archive, the first positive detection of X-ray emission from DQ Her has also been achieved; however the very low inferred luminosity,  $L_x \sim 10^{30} \text{ erg s}^{-1}$ , suggests that this is simply a detection of the chromosphere of the cool star in the system.

An intensive campaign to study the asynchronous AM Her-type star BY Cam was undertaken by Silber, with Fierce, Hammergren, Hoard, K. Olsen, Szkody, J. Morgan, T. Naylor (Keele), P. Mason (CWRU), E. Pavlenko, N.M. Shakhovskoy (Crimean), S. Shugarov (Sternberg), R. Rolleston (Queens), R. Ruotsalainen (Eastern Wash.), E. Schmidt (Nebraska), I. Andronov, and S. V. Kolesnikov (Odessa). At least 3 hours of photometry was taken on 40 nights over a two month period. From these data a beat period of 2 weeks was detected for the first time.

IUE and optical observations of BY Cam were studied by Zucker, Silber, J. Raymond (CfA), Mason, S. Vrtilik (Maryland), E. Schlegel (GSFC). The velocity of the strong UV line N V  $\lambda 1240$  was seen to vary at the orbital period with an amplitude of  $368 \text{ km s}^{-1}$ .

IUE and optical observation of AM Her were obtained by Silber, Raymond, Shakhovskoy, Mason, Andronov, and N. Borison (Special Astrophysical Observatory). They showed that there is a hot spot on the white dwarf surface during the low state, and that this spot is probably due to continued accretion.

S. Wachter and Margon obtained broadband photometry of the optical counterpart of GX349+2 (Sco X-2), an intense, low-mass X-ray binary "Z-source." There is evidence

for a  $21.7 \pm 0.3$  hr period of 0.14 mag half-amplitude, superposed on erratic flickering typical of Sco X-1 type objects. As with other Z-sources, caution will be needed to insure that the variations are truly periodic, and not simply due to chaotic variability observed over a relatively short time span.

Using *HST*, Anderson, Margon, and Downes (STScI) have obtained low resolution UV and optical spectra of the counterparts to the core X-ray sources in the globular clusters NGC 7078 and NGC 6712. Their small aperture Faint Object Spectrograph (FOS) data for the X-ray source counterpart AC211 in NGC 7078 confirm many features seen in earlier large aperture ground-based and *IUE* spectra, but some important differences are also evident (suggesting significant contamination in the earlier large aperture data). Their FOS data for the counterpart "Star S" in NGC 6712 are intriguing, as neither absorption nor emission are identifiable. The AC211 and "Star S" observations may presage a spectral diversity among the counterparts to X-ray bursters in globular cluster cores.

E. Deutsch, Margon, Anderson, and Downes also used multicolor *HST*/WFPC1 images of NGC 1851 to search for a counterpart to the strong X-ray source in that globular cluster as well. A color-magnitude diagram from their high spatial resolution U and B WFPC images confirms the ground-based result of Aurière *et al.* that there are no moderately bright objects having a marked UV-excess in the X-ray error box, and that the object known as "X1" is among the "best" of poor choices for the optical counterpart. However, their WFPC1 images also reveal additional objects within the X-ray box that were not resolved in the ground-based images, including objects with colors similar to those of "X1."

### 2.3 Interstellar Material and Ejecta

Balick, along with A. Frank and K. Davidson (U. Minn), completed a numerical model which accounts for the measured shape and expansion of the nebula surrounding the eruptive LBV star eta Carinae. They are now proceeding with the acquisition and analysis of new HST data on this most curious object.

Balick, along with A. Hajian and Y. Terzian (Cornell) are studying the ionization and abundances of gas expelled from the nuclei of planetary nebulae in order to determine if the gas has been dredged deep from within the stellar remnant. They are analyzing their very deep optical spectroscopic data of the jets, ansae, and halos of selected planetaries.

Balick, B. Rodgers, Hajian, Terzian, and Bianchi (STScI) have completed coordinated optical and IUE spectroscopic monitoring observations of the stellar nucleus of the planetary nebula NGC 40. This relatively bright WC8 star shows rapid spectroscopic variations in certain carbon lines, suggesting that it is ejecting blobs of material nearly continuously.

Beck-Winchatz, Böhm and A. Noriega-Crespo (IPAC) are studying the gas-phase abundances of metals (especially Fe and Ni) in a number of Herbig-Haro objects. The main purpose is to derive information about the destruction of dust grains in Herbig-Haro shock waves. The authors compare, especially, a large number of iron lines with the statistical

equilibrium predictions for Herbig-Haro models. These predictions have been drastically improved recently by the large number of collision strengths which have now been predicted by Zhang and Pradhan (1995, *A & A*, 293, 95) for  $\text{Fe}^+$ . Especially interesting results are found for the objects HH 255 and HH 43A.

Böhm and Solf (Tautenburg Obs.) continue to study the outflows in the immediate vicinity of T Tauri. They determine a detailed (empirical) model of HH 255 (Burnham's nebula), especially studying the coupling between the abrupt changes of the degree of ionization and the abrupt changes in the observable kinematics (mostly recognizable in the radial velocity dispersion and in the centroid radial velocity) of HH 255. Although HH 255 has a number of properties which do agree with Herbig-Haro shock waves other properties remain enigmatic.

## 2.4 The Galaxy

Stubbs, Pratt and collaborators (the MACHO collaboration) produced the first stringent limits on the MACHO content of the Galaxy's dark halo. Stringent constraints were established for halo lensing objects with masses between  $10^{-4}$  and 0.1 solar masses. The number of microlensing events this experiment has detected towards the Galactic Center now exceeds 85, and the optical depth towards the Galactic center is an important new ingredient in Galactic mass models. A number of exotic variants of microlensing events have now been detected, many prior to peak amplification (A. Becker).

Sullivan (together with J. Cordes of Cornell, K. Wellington of ATNF, P. Backus and S. Shostak of the SETI Institute, and M. Griffith) used the Parkes 210-ft radio telescope and the SETI Institute 10-million-channel receiver in June 1995 to do a SETI experiment at a great number of locations near the galactic center.

Baum and Hammergren are collaborating with R. M. Light (IPAC, Caltech) and other members of the HST-WFPC team on new WFPC2 observations in "Baade's Window," a field of relatively low obscuration about 4deg from the direction to the galactic center, to study populations in the Galactic bulge.

## 2.5 External Galaxies and QSOs

Hodge and B. Miller (Carnegie Inst.) published a study of the HII regions for four galaxies in and near the Local Group (WLM, LGS-3, UGC A86, and EGB 0427+63). The H II region populations of the galaxies have normal size and luminosity functions. The size scale factors indicate that the latter two are not members of the Local Group. Emission-line spectra provide elemental abundances for the brightest HII regions, which indicate that the O/H ratios are very low, about 7% of solar.

Miller and Hodge also obtained spectra of HII regions in three intermediate-luminosity galaxies of the M81 group, for which they found O and N abundances that fit the  $\log(\text{O}/\text{H}) - M(\text{B})$  relation; O abundances are typically 10% of solar.

Hodge, E. Wilcots (U. Wisc.) and L. Pastwick (UWyo.) completed an analysis of the massive stellar population of

the OB association LH 72 in the LMC. The association is  $\sim 5$  million years old, with its brightest stars having spectral types ranging from O6 V to B0 I.

Hodge, with Wilcots and Miller, used the VLA to map the properties of the H I gas in the Local Group galaxy IC 10. There is a highly-complex turbulent inner disk of gas that corresponds to the visible-light features and an extended outer halo of gas that is apparently falling into the disk. The galaxy shows unusually active star formation.

With W. Waller, S. Heap, E. Malumuth (all at GSFC) and others, B. Patterson and Hodge continued their HST study of the stellar components of giant H II regions in M33. For the six brightest member H II regions, they determined masses, luminosities, reddenings and ages from both ultraviolet and visual data. The brightest stars range from  $M(V) = -9.0$  (for CC 93) to  $-7.7$  (for IC 342) and ages average about 4.5 million years.

Working with F. Verter (GSFC), Hodge completed a study of the CO-to- $\text{H}_2$  conversion factor for very low heavy element abundance galaxies. It is found from the most extreme example searched (GR 8 with O/H about 3% solar) that the conversion factor clearly increases with decreasing metallicity.

L. Mendoza and Hodge obtained a series of CCD images with the APO 3.5m telescope of the Leo I galaxy to search for RR Lyrae variables in connection with coordinated observations being made by M. Mateo (UMich.) and E. Olszewski (UAriz.).

J. Collier obtained multi-color CCD images of nearby galaxies with the MRO 0.8-m telescope, finding that it is possible to isolate OB associations clearly and automatically, using objective methods (Principal Components Analysis and Cluster Analysis) to explore color space. This extends previous work of this nature published by Hodge, working with S. Adanti and R. Capuzzo-Dolcetta (both U. Roma) and P. Battinelli (Obs. Roma).

Patterson continued her investigation of the diffuse  $\text{H}\alpha$  emission in the galaxy M33, obtaining data from both the MRO 0.8-m and the APO 3.5m telescopes.

Sullivan (together with Griffith, and A. Wright and N. Tasker of ATNF) used the compact array of the Australia Telescope over a week to monitor for intensity variability  $\sim 100$  radio sources from the Parkes-MIT-NRAO survey that appeared to be variable from the original survey data. First indications are that very few of these in fact were variable on day-to-day time scales, but many are over a period of several years.

Baum and Hammergren, together with colleagues on the HST-WFPC team, completed their analysis of deep WFPC2 exposures of NGC 4881, which is a bright E0 galaxy about 18 arcmin from the center of the Coma Cluster. These observations were made to explore the possibility of determining the distance to Coma based on finding the "turnover" magnitude of the globular cluster luminosity function (GCLF), thereby directly linking Coma to objects in the Milky Way without involving intermediate distance markers such as the Virgo Cluster. Coma has a mean cosmological redshift of  $\sim 7200$  km/sec and is  $\sim 6$  times farther than Virgo, so it offers an opportunity to measure the Hubble Constant with

less uncertainty due to local motions. Counts indicate that there are about 195 globular clusters in NGC 4881 down to a threshold of  $V \approx 27.6$  mag, but they did *not* show evidence of having passed the GCLF turnover. The *minimum* distance to Coma is therefore inferred to be 108 Mpc (with a formal error of  $-11$  Mpc), which corresponds to a maximum  $H_0$  value of 67 km/sec per Mpc (with a formal error of  $+7$  km/sec per Mpc).

Baum and Hammergren together with E. J. Shaya (U. Maryland) studied a gravitational arc  $2.1''$  from the center of NGC 4881. They deduced a mass of  $\sim 2.5 \times 10^{10} h^{-1} M_\odot$  within  $750 h^{-1}$  pc of the NGC 4881 nucleus, and a core radius of  $350 h^{-1}$  pc for the dark matter component.

Baum, together with C. J. Grillmair (UCO/Lick) and several other HST-WFPC team members, reported 1992 WFPC1 observations of the nuclear regions of the brightest cluster ellipticals NGC 3311 and NGC 7768. They found the nuclei of both galaxies to be obscured by dust, with possible on going star formation in NGC 3311. They also found the core radius of the globular cluster system in NGC 3311 to be at least an order of magnitude larger than the core radius of NGC 3311's stellar light, suggesting the two populations may be dynamically distinct.

Baum is collaborating with C. J. Grillmair and S. M. Faber (UCO/Lick), E. J. Ajhar and T. Lauer (NOAO), and J. A. Holtzman (NMSU) on HST-WFPC2 observations of four globular clusters in M31 for the purpose of determining structural parameters (headed by Grillmair) and color-magnitude diagrams (headed by Ajhar). The four, all located in the M31 halo but differing in metallicity, are K58, K105, K108, and K219.

Baum is collaborating in a 3-color ( $UVI$ ) WFPC2 study of NGC 604 headed by D. A. Hunter (Lowell Observatory). NGC 604 is a giant H II region in the nearby Scd galaxy M33. Color-magnitude diagrams show a main sequence down to  $M_V \sim -1$  mag, or about  $6 M_\odot$ , and the estimated age is 3–5 Myrs.

## 2.6 Cosmology

Moore, Katz and Lake investigated the ‘over-merging’ problem using analytic results and new simulations designed to calculate destruction times of halos owing to numerical and physical dynamical effects. Over-merging is a term used to describe the failure of numerical experiments to identify galaxy halos, or substructure within dense environments in a universe dominated by cold dark matter. Substructure in these simulations is destroyed by the combined action of large force softening together with tidal heating by the cluster and encounters with other dissolving halos. In the limit of infinite numerical resolution, the survival of individual halos or substructure depends sensitively on their inner density profiles. Singular isothermal halos always survive at some level. However, if halos form with large core radii then the over-merging problem will always exist within dissipationless N-body simulations. In this case a dissipational component can increase the central density enabling halos to survive. Resolving the central density structure of objects in cosmological simulations is still an active research topic in our group.

Moore, Katz and Lake used high resolution numerical simulations to investigate the morphological evolution of galaxy clusters. In collaboration with A. Dressler (Carnegie) and A. Oemler (Yale), the results of these simulations were compared with HST images of galaxy clusters at redshifts  $z \sim 0.5$ , and CCD images of nearby clusters. Distant galaxy clusters contain a large population of star-bursting dwarf spirals which appear morphologically disturbed. This galaxy population is absent from nearby clusters which are dominated by dwarf elliptical galaxies.

“Galaxy harassment” (frequent high speed galaxy encounters) is a mechanism which can drive the observed evolution in the galaxy populations in clusters. The strong tidal shocks from repeated close encounters with large galaxies causes bursts of star-formation and provides a heating source which transforms the cold disks of dwarf spirals into prolate configurations closely resembling dwarf elliptical galaxies. Simulated images of galaxies match the disturbed disk galaxies in clusters at  $z \sim 0.4$ . Moore and collaborators predict that intermediate redshift clusters will contain many low surface brightness filaments and arcs which are the debris material from destroyed disks.

Galaxy harassment also provides a natural explanation for low redshift quasars with host galaxies much fainter than the Milky Way. Lake and collaborators found that more than 90% of the H I of gas rich dwarf spirals in clusters is driven to the center by efficient angular momentum transfer. This material can provide sufficient fuel to power a quasar in a low luminosity host galaxy.

Katz with D. Weinberg (Ohio State U.) and L. Hernquist (UCSC) simulated the cold dark matter (CDM) scenario (with  $\Omega = 1$ ) using a version of TreeSPH generalized for cosmological integrations. TreeSPH combines smoothed-particle hydrodynamics (SPH) with the hierarchical tree method for computing gravitational forces. Lagrangian hydrodynamics and individual time steps for gas particles provide the large dynamic range that is essential to study galaxy formation in a cosmological context. Radiative cooling assumes an optically thin, primordial composition gas in ionization equilibrium with a user-specified ultraviolet background. A phenomenological prescription for star formation gradually turns cold, dense, Jeans-unstable gas into collisionless stars, returning supernova feedback energy to the surrounding medium. In CDM simulations, some of the baryons that fall into dark matter potential wells dissipate their acquired thermal energy and condense into clumps with roughly galactic masses. The resulting galaxy population is insensitive to assumptions about star formation; they obtain similar baryonic mass functions and galaxy correlation functions from simulations with star formation and from simulations without star formation in which they identify galaxies directly from the cold, dense gas.

Katz, Hernquist and Weinberg followed the cosmological evolution of the intergalactic medium comparing to the properties of QSO absorbers. Their high-resolution calculation of the CDM model does a remarkable job of reproducing many of the observed properties of the Ly $\alpha$  forest. The distribution of HI column densities agrees with existing data to within a factor of  $\sim$  two over most of the range from  $10^{14} \text{cm}^{-2}$  to

$10^{22}\text{cm}^{-2}$ ; i.e., from unsaturated Ly $\alpha$  forest lines to damped Ly $\alpha$  systems. The equivalent width distribution matches the observed exponential form with a characteristic width  $W_* \approx 0.3 \text{ \AA}$ . The distribution of  $b$ -parameters appears consistent with that derived from QSO spectra. Most of the low column density absorption occurs in large, flattened structures of moderate or even relatively low overdensity, so there is no sharp distinction between the Ly $\alpha$  forest and the ‘‘Gunn-Peterson’’ absorption produced by the smooth intergalactic medium. Comparison between simulations and high-resolution QSO spectra should open a new regime for testing theories of cosmic structure formation. They find that the damped Ly $\alpha$  and Lyman limit absorbers are associated with forming galaxies. Damped Ly $\alpha$  absorption,  $N_{\text{HI}} \geq 10^{20.2}\text{cm}^{-2}$ , arises along lines of sight that pass near the centers of relatively massive, dense protogalaxies. Lyman limit absorption,  $10^{17}\text{cm}^{-2} < N_{\text{HI}} < 10^{20.2}\text{cm}^{-2}$ , develops on lines of sight that pass through the outer parts of such objects or near the centers of smaller protogalaxies. The number of Lyman limit systems is less than observed, while the number of damped Ly $\alpha$  systems is quite close to the observed abundance. Damped absorbers are typically  $\sim 10$  kpc in radius, but the population has a large total cross section because the systems are much more numerous than present day  $L_*$  galaxies. Their results demonstrate that high column density systems like those observed arise naturally in a hierarchical theory of galaxy formation and that it is now possible to study these absorbers directly from numerical simulations.

Quinn and Katz, with G. Efstathiou (Oxford), studied the formation of dwarf galaxies in the presence of a UV background radiation field. It has been argued that a UV photoionizing background radiation field suppresses the formation of dwarf galaxies, and may even inhibit the formation of larger galaxies. In order to test this, they performed gas-dynamical simulations of the formation of small objects in a CDM universe with and without a photoionizing background. The objects are selected from a collisionless simulation at a redshift of 2.4, and rerun at higher resolution including the effects of gas dynamics and using a hierarchical grid of particles. Five objects, each with a circular speed of  $46 \text{ km s}^{-1}$  were simulated. The presence of the photoionizing background has only a small effect on the amount of gas that collapses in these objects, reducing the amount of cold collapsed gas by at most 30%. Analysis of the smaller objects found in the higher resolution simulation indicated that the photoionizing background only significantly affects the formation of objects with a virialized halo mass less than  $10^9 M_{\odot}$  and circular speeds less than  $23 \text{ km s}^{-1}$ . However, the ionization balance is greatly changed by the presence of the background radiation field. Typical lines of sight through the objects have 4 orders of magnitude less neutral hydrogen column density when the photoionizing background is included.

Moore, Lake, Stadel, Quinn, Katz and F. Governato (Univ. of Rome ‘‘Tor Vergata’’) studied large scale simulations of critical and low  $\Omega$  CDM universes. High resolution simulations including hydrodynamics, have been run on a small sample of Local Groups in a CDM (with  $\Omega = 1$ ) to study galaxy formation and satellite dynamics on scales of a

few tens of kpcs. The two dominant galaxies in the simulations have hot gaseous halos able to strip satellites of their gaseous content, in agreement with recent models of the formation of the Magellanic stream by Moore & M. Davis (UC Berkeley).

M. Rugers and Hogan continued their study of deuterium in high-redshift QSO absorbers. They isolated several situations where the D candidate was too narrow to be typical H Ly $\alpha$  line masquerading as deuterium. By eliminating the possibility of such interlopers, they showed that the primordial deuterium abundance  $D/H \geq 10^{-4}$ , in agreement with predictions of Big Bang nucleosynthesis and implying a rather low cosmic baryon density which requires galaxy halos to be made of non-baryonic dark matter.

D. Ingram and Hogan are using the APO 3.5-m telescope to take spectra of companions of QSO absorbers for studies of galaxy correlations and evolution at high redshift. Ingram developed and is using for this project a fast lithographic technique for making slit masks for the DIS imaging spectrograph.

Reiss, Diercks, Stubbs and Hogan started a monitoring program on the 3.5-m telescope as part of an international effort to find and study high-redshift supernovae.

Hogan proposed a new theory which uses two modes of a single multicomponent global scalar field to make both scale-invariant cosmic fluctuations and cosmic dark matter. The theory predicts an isocurvature component of fluctuations on small scale, and non-negligible (‘‘tepid’’) peculiar velocities in the dark matter. Further details are being studied by Hogan with E. Bradford and L. Buchman.

Rodrigues-Williams completed her thesis on lensing-induced statistical associations of galaxies and background QSO’s. Rodrigues-Williams and P. Saha (MSSSO) considered the ‘‘improper motions’’ resulting from variable micro-amplification of different components of an unresolved gravitational lens.

Hogan and M. Bolte (UCSC) compared the best estimates of the ages of the oldest stars with the expansion rate of the universe, and concluded that, within statistical errors, the flat, matter-dominated universe is ruled out. Open universes or flat ones with cosmological constants are favored, implying that the expansion will continue forever. Hogan completed a review of the Hubble constant for the Review of Particle Properties. He also organized a conference on galaxy formation at the Aspen Center for Physics, which formed the basis of a review (with M. Fukugita, Kyoto and P. J. E. Peebles, Princeton).

## 2.7 Miscellaneous

Brownlee was elected to the National Academy of Sciences, who also awarded him the J. Lawrence Smith Medal.

Stubbs was named a Packard Fellow by the David and Lucille Packard Foundation. This generous five-year fellowship provides a total of \$500,000 in research funding.

Hodge continued as Editor of the *Astronomical Journal*.

Margon continued as Chair of the Board of Governors of the Astrophysical Research Consortium (ARC), Chair of the NASA Headquarters High Energy Astrophysics Management Operations Working Group, as well as a member of the

NASA Headquarters Astrophysics Subcommittee of the Space Science Advisory Committee, and of the AURA Space Telescope Institute Council (STIC). He was also selected as the new Chairman of the Board of Directors of AURA.

Sullivan became Chair of the AAS Historical Astronomy Division and Vice-President of IAU Commission 50 (Protection of Observatory Sites).

### 3. RESEARCH TOOLS

#### 3.1 Instrumentation

The UW Telescope Engineering Group (Waddell, Mannery, Siegmund, Owen, Hull, Limmongkol, Evans) continue to provide the primary engineering support for the Sloan Digital Sky Survey (SDSS) 2.5m telescope, optics, structures, control system, and portions of the multifiber spectrograph. The telescope has been delivered and installed, and completion of the optics is expected shortly.

A team led by Stubbs has started construction on a wide-field mosaic CCD imager for the 3.5m APO telescope, funded by a generous grant from the Seaver Institute. When complete, this instrument will be used to conduct a variety of observational cosmology programs.

The Global Microlensing Alert Network (GMAN) is being managed from the University of Washington by A. Becker. This is a set of small aperture telescopes around the world used to track the progress of gravitational microlensing events that are detected in real time.

Balick, along with W. Kimura and G. Kim (STI Optronics, Bellevue, WA), have completed studies on the optimum methods for cleaning large astronomical mirrors. They have completed studies on the efficacy of cleaning with CO<sub>2</sub> ice and pulsed ultraviolet lasers. They find that lasers hold the greatest potential for maintaining very large mirrors at high levels of performance, especially at infrared wavelengths.

Silber, Mannery, Stubbs, and C. Hastings are building a slit jaw viewer for the Double Imaging Spectrometer on the APO 3.5m telescope.

A new automated, 6-position filter slide was installed at the MRO 0.8-m telescope by Morgan. A. Dolphin has written and tested software for an MRO autoguider and Morgan with

the help of Mannery has constructed optics for this autoguider. The autoguider is now in routine operation at the telescope. With funds provided by J. Sahr of the Electrical Engineering Department, Morgan and F. Lind have installed a microwave link between MRO and Central Washington University. This link now allows continual internet access to MRO observers. Morgan has also worked on the construction of a new 1024 x 1024 CCD camera for use at MRO.

#### 3.2 Numerical Methods

Quinn, Katz, Lake and J. Stadel have developed and implemented a multistep symmetric integration algorithm for N-body simulations. Testing on isolated clusters show much better energy conservation than non-symmetric methods. Whether this is also the case for cosmological clustering simulations is unclear.

Periodic boundary conditions are essential for cosmological simulations. Many tree codes use high-order representations of the force (quadrupole, octapole, etc.) to achieve higher accuracy. However, past implementations of the Ewald method only used monopoles requiring that these gains be forsaken in cosmological simulation. Quinn and Stadel generalized the Ewald method to arbitrary order and have implemented it through hexadecapole in a production code.

The current version of the gravity code written by Stadel and Quinn, kd-grav, is now running on both the IBM SP-2 and the Cray T3D. Performance is excellent. The speedup is within 85% of linear on 128 nodes. The sustained rate is more than 10 Gigafllops on the machines available at National Centers. They have done "survey runs" of 3 million particles and are preparing a 47 million particle run to be used for data assimilation for the SDSS.

Quinn has joined a team at Princeton University working on the development of the photometric pipeline for the SDSS. His work has included developing a faster faint object finder, a more efficient method for masking bad pixels, and object classification.

Craig J. Hogan, Chair